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Design of a Wearable Device for ECG Continuous Monitoring Using Wireless Technology

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Abstract—**This project focuses on the design and implementation of an intelligent wearable device for ECG continuous acquisition and transmission to some remote gateway using Bluetooth technology. The acquisition device has been designed for having very low power consumption and reduced size. The Analog Devices' ADuC831 Micro-Converter for achieving the analog to digital conversion and the CSR's BlueCore2 chip for the Bluetooth transmission are the core of the device. The designed device is an important component of a complete prototype for remote ECG continuous monitoring of patients with diverse cardiac diseases.**

Keywords—**ECG, Wearable Technology, Continuous Monitoring, Wireless Communication, Bluetooth**

I. Introduction

The monitoring of biomedical signals in chronic patients, elderly person even in healthy patients without serious diseases is a Telemedicine application that has gained a great importance in recent years [1]. These monitoring environments require the use of wearable devices supplied with small batteries. Obviously this type of devices must have low power consumption, reduced dimensions and minimum weight. Moreover, they must be easy to use and its monitoring function must be achieved with the lowest influence in the patient unchanging theirs quality of life [2].

The wireless transmission technologies (GPRS, GSM, Bluetooth, Wi-Fi…) also play an important role in these monitoring devices replacing all wired connection with a gateway for transmitting the information of the biomedical signals [3]. Likewise these monitoring services need the development of new electronic systems that are able to provide the signal acquisition and conditioning front-end together wireless technology support. There are some projects that have been worked in this way. Thus, a GPRS based system for ECG monitoring is described in [4]. Likewise the readers can get more info about new projects and commercial devices related to remote monitoring of bioelectrical signals using any type of wireless transmission technology in [5-8].

This paper addresses the design of an intelligent wearable Holter with low power consumption and reduced size for the continuous monitoring and wireless transmission of ECG signals using Bluetooth technology. This device is part of a telemonitoring system for the visualization, processing and/or storage of the ECG signals acquired by a wearable sensor using a gateway as a laptop, PDA or even a GPRS mobile phone for the retransmission to some hospital unit (figure I.1).

The Holter has been designed for having very low power consumption allowing the use of a rechargeable battery for providing the power supply, and with minimum number of components in order to reduce its dimensions. The device has two operation modes with different monitoring requirements. The continuous operation mode is used with patients that require a real-time monitoring. On the contrary, event mode is used as classical ambulatory Holter. In this way the monitored patient can stop the acquisition when he suffers any cardiac event so that a programmed time before and after the event is just recorded.

The designed Holter uses Bluetooth technology in the communication with the gateway. This short-range technology is a very cost-effective way to design mobile systems with a maximum data transfer rate of 723 Kbps and low power consumption. Moreover, the Bluetooth technology is a universally adopted standard allowing compatibility among devices of different manufacturers thanks to the called "Profiles" [9,10]. The CSR's BlueCore2-Flash chip has been used to achieve the Bluetooth communication. The limitations of this chip used in similar devices are indicated in some previous research projects [11]. For this reason the Analog Devices' ADuC831 MicroConverter has been included in this project.

The remainder of this paper is organized as follows. The next section describes the hardware used with special attention to the ADuC831 MicroConverter and BlueCore2-Flash chip. Section III explains the most important aspects related to its operation. Finally, an overview of the power consumption and conclusions are given in Section IV and V.

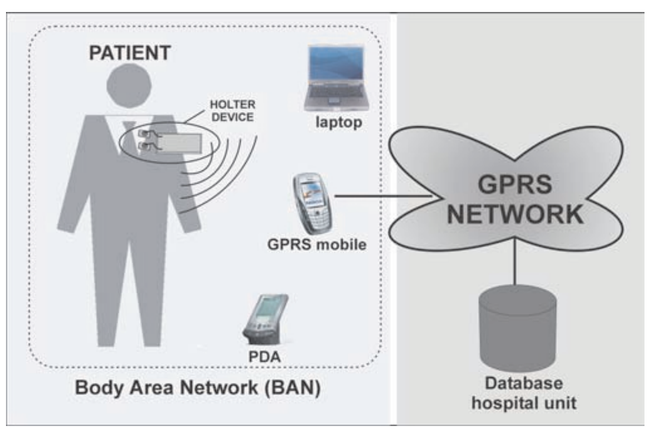

Figure I.1. Complete telemonitoring system

II. HARDWARE DESCRIPTION

The device consists of various hardware blocks (figure II.1) that are explained in the following sections with special attention to the ADuC831 MicroConverter performing the analogue to digital conversion of the ECG signal and the BlueCore2-Flash chip providing the Bluetooth communication with a remote device. All blocks has been chosen and designed for obtaining the lowest power consumption because the power supply by a rechargeable battery is provided [12].

II.1 ANALOGUE FRONT-END

The first block is a very low power analogue front-end which is composed of several amplifier and filter stages [13]. This block conditions the ECG signal for its later A/D conversion. One of the stages is a high pass filter with a cut-off frequency of 0.05Hz that removes the DC offset of the signal. Subsequently an antialiasing low pass filter with a cut-off frequency of 100Hz and a Notch filter (50Hz – 60Hz) for rejecting the power line interferences are used. In this analog block, the gain can be user-configured and a 0.8 V DC offset has been added to the signal for reaching all input range of the ADC. The total power consumption of the analogue front-end is 500µA.

II.2 ADuC831 MCRO-CONVERTER

The ADuC831 Micro-Converter is a fully integrated data acquisition system including among other electronic topologies, a multi-channel 12-bit ADC with Direct Memory Access (DMA), an 8052 programmable 8-bit MCU and the capability to access up to 16MB of external data memory (SRAM) [14]. The micro-controller also includes on-chip digital peripherals as four 8-bit programmable I/O ports, external interruptions for detecting user events, three timers/counters and serial ports I^2C, SPI and UART. The chip is specified for 3V operation with some power-saving modes for getting the lowest power consumption in the mobile Holter device. Table 1 shows some ideal power consumption values with a clock frequency of 11.0529MHz used in our design.

The ADuC831 microcontroller is the intelligent core of the device and it performs several tasks. It carries out the analog to digital conversion of ECG signal acquired by the front-end block (correctly conditioned for getting the most out of 2.5V input range of ADC) with a sampling frequency of 1 KHz. On the other hand, the microcontroller uses the UART serial interface with a bit rate of 115200bps for being connected with the BlueCore2-Flash chip, making possible the exchange of information between the mobile Holter and the gateway using Bluetooth technology. Furthermore, the micro-controller accesses to an external SRAM memory for recording the ECG in event mode. The HM62V8512 model of Hitachi has been used in this design [15]. The capacity of this memory is 4 Mbit allowing the storage of up to four minutes of ECG signal. The power consumption of this memory is 2mA. In addition two bus switches with a power consumption of 20µA are used for accessing to this memory because the ADuC831 address/data ports are multiplexed.

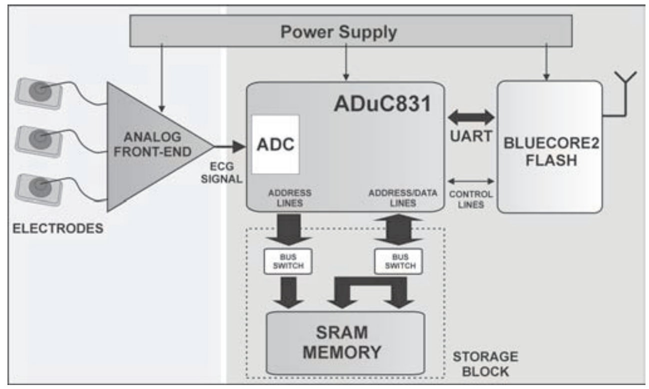

Figure II.1. Block diagram of the Holter device

Three out 4 I/O lines in the microcontroller are used. One of them is an external interruption line that can be activated by the user (using some type of electro-mechanic component) for stopping the sampling process in case of suffering a cardiac event. Another two lines are control lines used for the communication between the microcontroller and the Bluetooth chip. One is activated by the BlueCore2-Flash chip indicating either establishment or loss of Bluetooth connection with the remote device and another is used by the micro-controller in event mode indicating there are ECG data stored in the SRAM memory that must be transmitted to some remote device.

Table 1. POWER CONSUMPTION OF THE ADuC831

State	Power consumption
Normal mode	10 mA
Idle mode	6 mA
Full power-down mode	15 µA

II.3 BlUECORE2-FLASH CHIP

The BlueCore2-Flash is a single chip radio and base band IC used in Bluetooth 2.4GHz systems and it's been designed to reduce the number of external components required [16]. This device has available a 16-bit RISC processor with an internal FLASH memory where the Bluetooth Protocol Stack and application code are stored and run. The chip includes digital peripherals as programmable I/O terminals (PIO lines) and serial communication interfaces (I^2C, SPI, USB and UART) for getting the connection with external devices. It also has analog input lines connected to an 8-bit ADC used commonly for monitoring the power supply. The chip is specified for 3V operation with a power consumption that depends on the chip state, the tasks that must be run and the transmission bit rate. It also has a very low power state (Deep Sleep) where the chip remains while there is not any task to run. Some power consumption data are shown in table 2.

The BlueCore2-Flash chip uses the UART interface for working like a "wireless bridge" between the gateway and the microcontroller. The chip doesn't perform any processing of data transferred between these two devices.

Two PIO lines are used as control lines connected to the microcontroller. One of them is configured as output line for notifying if a Bluetooth connection exists, just as it's been mentioned in the previous section. Another PIO line is configured as input and the ADuC831 chip in event mode activates it. The activation of this line makes the BlueCore2-Flash to search some valid remote device for transmitting the ECG information of the event suffered by the user.

Table 2. POWER CONSUMPTION OF THE BlueCore2-Flash chip

State	Power consumption
Data transfer 115.2 Kbps	7 mA
Data transfer 720 Kbps	50 mA
Deep Sleep	20 µA

III. OPERATION DESCRIPTION

This section describes the most important aspects related to Holter's operation as the establishment of Bluetooth connection, the communication protocol used between devices and operation modes.

The security plays an important role because personal details (ECG information) are managed. It's necessary to ensure all connections of the Holter device will be establish exclusively with authorized people's remote devices (doctors, health workers, user). Moreover, among all authorized people, only those ones directly joined with the user (the specialist, for example) must receive correctly the patient's information.

III.1 BLUETOOTH CONNECTION AND COMMUNICATION PROTOCOL

The communication between Holter and remote receiver requires a Bluetooth connection. During the establishment of this connection, data encryption and device authentication are the security mechanisms imposed to the system. A PIN code request in the authentication process is used for establishing a success connection. The PIN code of the Holter devices (each device has a sole code) must be known by the health workers with access to them, avoiding the connection of others unauthorized Bluetooth devices.

Nowadays the Bluetooth standard has not a specific profile for this type of biomedical applications. For this reason, the Holter application uses the Serial Port Profile emulating a wireless serial communication. For getting the correct exchange of information between the Holter device and the remote receiver it has been needed to develop a customized communication protocol based on various commands. Some commands of this protocol and the function performed are indicated below.

- Transmitter Configuration Command: the Holter device sends this command indicating its characteristics: ADC resolution, capacity of SRAM memory…
- Holter Configuration Command: the remote device sends it with the appropriate parameters for configuring the operation of the Holter device.
- Acquisition Start Command: the remote device indicates Holter device must start the sampling process.
- Acquisition End Command: the remote device indicates Holter device must stop sampling.

Additional security is obtained by encryption of all transmitted data. This process is made with a pseudo-random key obtained from a sole user's identification number.

III.2 OPERATION MODES

This wearable device has two operation modes: continuous mode and event mode. These modes are explained below.

CONTINUOUS MODE

Two internal memory blocks are reserved for the continuous storage of the data after A/D conversion. When one of these blocks is full, the transmission of its samples is accomplished while the conversion process continues storing data in the other block. The size of these blocks must be suitable for getting an efficient exchange of the information and for obtaining a delay between two consecutive blocks not too large. Moreover, this conversion process is achieved using DMA mode so that the micro-controller is free for running any additional ECG signal processing.

The process explained before can be only interrupted because of two reasons: a request by the remote device or the loss of Bluetooth connection. In any case, the microcontroller must stop the sampling process. Moreover, if the reason is the loss of connection, the processor goes into a very low power consumption state where it remains waiting a new connection.

EVENT MODE

The conversion process uses only one block of the external SRAM memory for storing data. The size of this memory block depends on a register time interval, which is user's programmable. The reserved block is filled up in a cyclic way until the appropriate external interruption line (section II.2) is activated. In this situation, the sampling process continues during a half register time interval and is stopped when this time's elapsed. Therefore, ECG signal information of the event in the external memory is stored.

Unlike continuous mode, the Bluetooth connection is not necessary once the Holter device's been configured and is running. The device will go into a middle power consumption state and it will continue acquiring the ECG signal until the external interruption line used for detecting user's events is activated. When this happens, the acquisition device starts a search of valid remote devices for transmitting the stored data. If the Holter device doesn't find any receiver it will go into a very low power consumption state waiting some Bluetooth connection. When this connection exists the device will warn about this data are stored.

IV. POWER CONSUMPTION

One of the most important aspects in the design of the device is the power consumption. All blocks of this device have been designed and selected in order to reduce the total power consumption. The states of the Holter and the tasks that must be carried out have also influence in the power consumption. Table 3 shows some power consumption values depending on Holter's operation modes. The rechargeable battery used in the design with these values of power consumption provides autonomy of 57 hours in continuous mode and 150 hours in event mode.

Table 3. POWER CONSUMPTION OF THE HOLTER DEVICE

State	Power consumption
Waiting connection	0.6 mA
Continuous mode	17.5 mA
Event mode (Sampling process)	6.5 mA
Event mode (Event suffered)	0.6 mA

V. CONCLUSION

The wearable Holter has been designed in order to improve the present ECG continuous monitoring devices. The design and selection of the electronic components and an efficient software implementation provide a device with great autonomy, reduced dimensions and minimum weight. These features lead to a device easy to use improving patient's quality of life. Limitations and restrictions found in previous research projects and commercial systems have been overcome with the use of a microcontroller. This microcontroller has allowed to perform ECG signals analogue to digital conversion, arranges the exchange of data with Bluetooth device and will permit to implement additional ECG signal processing as heart rate, R-R segment, etc. Moreover, the functionality of the Holter makes feasible its use in multiple health environments with different monitoring requirements.

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